Inaccuracies in weather data and their effects on crop growth simulation results. I. Potential production

Nonhebel, Sanderine

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Inaccuracies in weather data and their effects on crop growth simulation results. I. Potential production

Sanderine Nonhebel

Department of Theoretical Production Ecology, Agricultural University, PO Box 430, 6700 AK Wageningen, The Netherlands

ABSTRACT: In weather data sets used by crop modellers, irregularities occur as inaccuracies in data or as missing values. In this investigation, the effect of such irregularities in temperature and global radiation data on simulation results is studied for a spring wheat crop growth simulation model. From the literature, the inaccuracy in temperature and global radiation data was estimated to be 1 °C and 10% respectively. Systematic over- or underestimation of the data using these values resulted in deviations in simulated yield of about 10%. Four methods of estimating missing values were compared: use of average values over 30 yr, over 1 mo and over 10 d, and use of daily data from another meteorological station. When all daily data were replaced by estimates, data from a nearby station gave the best results: only a small deviation in simulated yield was found. The use of averages resulted in overestimations of yield of up to 35% in some years. For global radiation data the effect of estimates based on sunshine duration data was also considered; use of these data gave a better result than data from a nearby station. When only 10% of the daily temperature and radiation data were replaced randomly by estimates, no effects on simulation results were found.

KEY WORDS: Weather data · Crop-growth simulation model · Potential production

INTRODUCTION

Crop growth and yield are largely determined by weather conditions during the growing season. Therefore, in crop growth simulation models the most important relations between weather and crop growth are quantified, and weather data are important input values for these models. Crop growth models differ in their input requirements. Most of them require data on (air) temperature, radiation and precipitation on a daily or hourly basis, while others also require data on wind speed and vapour pressure (Whisler et al. 1986). The number of sites from which hourly weather data can be obtained is very limited, so that possibilities for applying models on a hourly basis are quite restricted. Daily weather data can be obtained from nearly all meteorological stations, and thus crop growth models requiring daily data as input are used more frequently.

In modelling practice, weather data are obtained from databases and are usually accepted at their face value. This is not realistic. Like all measured values, weather data are subject to inaccuracies and, since models are sensitive to weather data used as input, inaccuracies in weather data can affect the simulation results. The quality of crop growth models has improved over the last few decades and some models are able to simulate well the production observed in the field. At the current stage of crop model development, it is important to know whether the difference between observed and simulated growth is due to errors in weather data or instead to incorrect simulation of crop growth. Therefore, in this study frequently occurring irregularities in weather data sets are discussed and their effects on simulation results are investigated.

Several sources of irregularities in weather data can be distinguished. Firstly, there is deviation in measured values due to inaccuracy of the instruments. Another source of error is the fact that meteorological data are recorded at a limited number of sites. In general, field experiments are not located in the immediate vicinity of the site where meteorological data are recorded. This difference in locations may mean that the weather conditions are not the same.

The occurrence of missing values in data sets is another problem. Due to breakdown of instruments or to problems with the data-collecting computer, the value of a weather variable may not be recorded for several days. In the worst case there are no data available at all. Crop growth models require data for every day, so the missing values have to be estimated. Depending on the method used, the estimated value can deviate considerably from the actual one.

In this study, the magnitude of the deviation between the recorded value at a meteorological station and the one occurring in a nearby field experiment is estimated on the basis of the literature, and various estimation methods are compared. The effects of these inaccuracies in weather data and estimation methods on simulation results of a spring wheat crop growth model are examined. The model simulates potential and water-limited production. In the former, production is determined by crop characteristics, radiation and temperature, and in the latter by limited availability of water as well. For both production levels the crop is supposed to be free of pests, diseases and weeds, and optimally supplied with nutrients (de Wit & Penning de Vries 1982). The model is able to accurately simulate production observed in the field (Nonhebel 1993).

This paper focuses on errors in temperature and global radiation data and their effect on simulated potential production. The results are discussed separately for temperature and global radiation data. In the companion paper (Nonhebel 1994a, this volume) the effects of errors in weather data on water-limited production are discussed.

For an analysis of the effect of using time-integrated average data instead of daily data on simulated yield in different parts of the world, see Nonhebel (1994b); the effects of climatic change on simulated crop yield are considered in Nonhebel (1993).

MATERIAL AND METHODS

Simulation model. A spring wheat version of SUCROS87 (Simple and Universal CROp Simulation model; Spitters et al. 1989) was used. The core of this model is a calculation procedure for canopy photosynthesis and respiration, based on processes at the organ level. The model operates with time intervals of 1 d, but allows for the diurnal course of radiation. The allocation of dry matter production among the different plant organs depends on the stage of plant development. SUCROS87 requires daily weather data on minimum and maximum air temperature and on global radiation in order to simulate potential crop production.

This spring wheat version of SUCROS87 simulates crop growth and development from sowing to maturing of the crop. Development of the crop is driven mainly by temperature: from sowing to emergence, according to Porter (1987); from emergence to heading, according to Miglietta (1991); and from heading to maturing, according to van Keulen & Seligman (1987). Dry matter distribution is simulated according to van Keulen & Seligman (1987). The sowing date of the crop was set as March 11 and a variety adapted to Dutch conditions was used.

Crop production during the grain filling period is sink limited, which implies that weather conditions during this period hardly affect final yield (= grains). The size of the sink (the number of grains) is determined during the vegetative period of the crop (Spiertz & van Keulen 1980), and conditions during this part of the growing season have a large effect on final yield. For a high final yield a long vegetative period under high radiation levels is required. Therefore much attention is paid to the effects of inaccuracies in weather data on simulated growth during the vegetative period of the crop.

Air temperature influences a number of processes in the simulation model. The most important of these is the development rate of the crop, through which temperature determines duration and timing of the growing season. Temperature also affects assimilation rate, death rate of leaves and maintenance respiration. In general, the relation between temperature and the rates mentioned above is not linear.

In contrast with temperature, radiation affects only 2 processes in the simulation model: photosynthesis and transpiration. In this paper only its effect on photosynthesis is considered (potential production). Its effect on water-limited production through controlling transpiration is discussed in Nonhebel (1994a).

Meteorological data. The starting point of this study was a data set with daily weather data from Wageningen, The Netherlands (Fig. 1) for the period 1954 to 1987. The set contains daily values for minimum air temperature (°C), maximum air temperature (°C), total global radiation (J m^{-2} d^{-1}), total precipitation (mm), vapour pressure at 09:00 h (mb) and average wind speed (m s^{-1}). The data were collected at the meteorological station Haarweg, of the Wageningen Agricultural University; the station is a climatological station of the Royal Netherlands Meteorological Institute (KNMI).

Inaccuracy in data. The difference that could exist between recorded values at the meteorological station and values occurring in a nearby field experiment was estimated for all variables. Only differences that could be expected when measurements were taken accord-

Fig. 1. The Netherlands: location of the sites mentioned in the text. (1) Wageningen, (2) De Bilt, (3) De Kooy

ing to the regulations of the World Meteorological Organization (WMO 1983) were considered. The very large errors resulting from insufficient maintenance or improper set-up of the instruments were not taken into account. The effect of the inaccuracy on simulation results was determined by making 3 simulation runs with the model: one with the original data set, one with a data set in which the variable of interest was diminished by its expected inaccuracy and one with a set in which this variable was increased by the inaccuracy. All other elements were kept unchanged.

Estimation of missing values. Four methods were considered for estimating missing values: use of (1) averaged monthly values over 30 yr (climatic averages), which, with only 12 values per weather variable, are relatively easy to obtain; (2) monthly averages, which are published in most monthly reports of national meteorological organizations; (3) average values over 10 d, also published in the monthly reports; and (4) daily data from another meteorological station. These methods are frequently used in crop growth simulation practice. Simulation runs were made in which all daily values of the variable of interest were replaced by estimated values.

In this study the average values were not obtained from the literature, but were derived from the data set with daily data. The average values were used as follows: the average value per month for each variable was calculated from the original weather data set. It was assumed that these average values occurred on the 15th of every month and that on the intervening days the value for the element could be derived by linear interpolation. The same method was applied for averages over 10 d, but then the average values were assumed to occur on the fifth day of the interval. Climatic averages were derived using the monthly averages for the period 1954 to 1983. Use of averages over 30 yr implied that in all years the variable of interest was the same; the years varied only with respect to the values of the other weather variables.

The effect of using another meteorological station as the source of weather variables was investigated by replacing data from Wageningen with data from De Bilt (Fig. 1). De Bilt is the nearest synoptical station of the KNMI. The distance between Wageningen and De Bilt is only 40 km and both sites are located in the same climatic district. Daily weather data from De Bilt were available for the period 1961 to 1987.

The effect of using data from a station in another climatological district was studied by using weather data from De Kooy (Fig. 1). De Kooy is also a synoptical station of the KNMI and is located in the northwestern part of the country, very close to the North Sea. The weather in this region is strongly influenced by the sea, resulting in, for instance, higher radiation levels and lower temperatures in spring and higher temperatures in autumn (Können 1983). Weather data from De Kooy were available from 1976 to 1985. The distance between De Kooy and Wageningen is only 130 km.

In general data are not missing for a complete year, but only for a period in a year; therefore, the effects of only a few missing data were also studied. Using a random number generator, 10% of the daily values during the crop growing period were replaced by estimates based on climatic averages.

TEMPERATURE DATA

Potential sources of inaccuracy

The temperature of a system is seldom measured directly. In general a thermometer is added to the system, and when the new system has reached an equilibrium the temperature of the thermometer is recorded (Bell & Rose 1985). Several instruments and techniques exist to determine temperature of a system. The accuracy of the instruments varies from 0.001 to 1.0 K (for detailed information on techniques and instruments see Fritschen & Gay 1979 and Bell & Rose 1985). Due to the poor coupling between atmosphere and thermometer it is difficult to achieve an equilibrium situation between the thermometer and the surrounding air, and errors associated with thermometer exposure can be an order of magnitude greater than the calibration error of the instrument, according to Bell & Rose (1985); they conclude that only a few thermometers have an accuracy of less than 1 °C. Radiation in particular can cause large temperature differences between the thermometer and the air: the temperature of a thermometer under direct sunlight can be up to 25 °C higher than that of the surrounding air (WMO 1983). For this reason air temperature is measured in thermometer screens. The design of the screen affects the temperature measured and differences of 1 °C have been found between various screen types (Sparks 1972, Huband et al. 1984).

Temperature is not distributed homogeneously over an air mass. Air temperature is affected by soil type, ground cover, the existence of water surfaces, etc. Differences in air temperature of several °C have been observed over distances of less than 1 km (Heldal 1980, Können 1983).

Thus, it is quite likely that air temperature above the field experiment area deviates by 1 °C or more from the value measured above the grass surface of the meteorological station. The effect of an inaccuracy of 1 °C in temperature data on simulation results was studied by increasing or diminishing both maximum and minimum air temperatures by 1 °C.

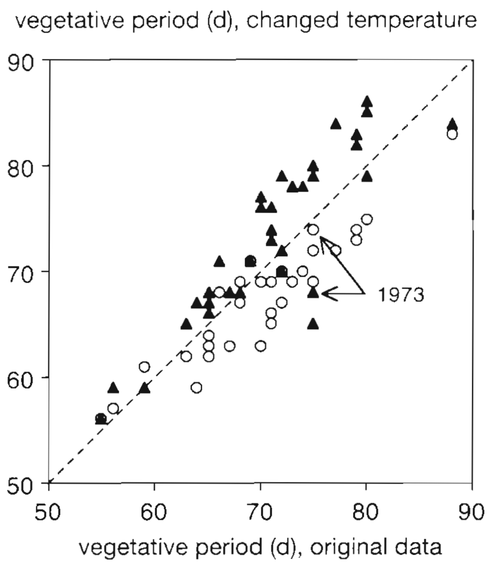

Fig. 2. Comparison between duration of the spring wheat vegetative period simulated with the original data set (Wageningen, 1954 to 1987) and duration of this period when temperature in this data set was underestimated (▲) or overestimated (O) by 1 °C

Results and discussion

The effect of a 1 °C deviation in temperature on simulated duration of the vegetative period (number of days between crop emergence and flowering) is shown in Fig. 2. Changes in duration of up to 10 d were found. In most years overestimation of temperature led to a shorter vegetative period, and underestimation to a longer one. However, in one-fourth of the years the opposite effect was found. In 1973 both over- and underestimation of temperature led to underestimation of vegetative period duration. This indicates that duration of the vegetative period is not linearly related to temperature.

To achieve better insight into the effect of temperature changes on duration of the vegetative period, simulation runs were made in which temperature was increased in increments of 0.2 °C from −6 °C to +6 °C. So, in the first run, daily minimum and maximum temperatures for the whole growing period were diminished by 6 °C, in the second run by 5.8 °C, etc. This was done with daily data from 1973 and with the climatic averages. Large differences in the effect of temperature deviations between average and daily weather were found (Fig 3) In the simulation runs with 30 yr climatic averages, overestimation of temperature resulted in a decline in duration of the vegetative period, underestimation up to 2 °C resulted in an increase, and larger underestimations had no further effect on the duration. With the 1973 data, however, an underestimation of 1 °C in temperature resulted in a sharp decline in the duration of the vegetative period.

The effect of a deviation of 1 °C on simulated yield (grains, dry matter) is shown in Fig. 4; changes in yield of up to 10 % were found. In about half of the years underestimation of temperature resulted in underesti-

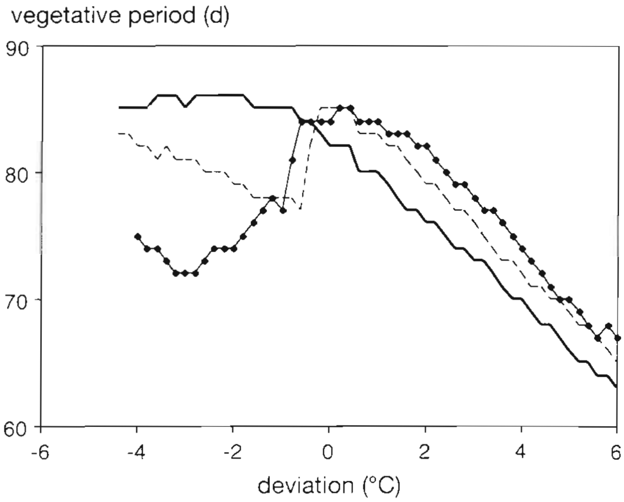

Fig. 3. Effect of a deviation in temperature of up to 6 °C on simulated duration of the spring wheat vegetative period, when climatic averages (——), daily weather data from 1973 (◆-◆-◆) and climatic averages with adjusted temperatures (see text) (- - - -) were used as input data

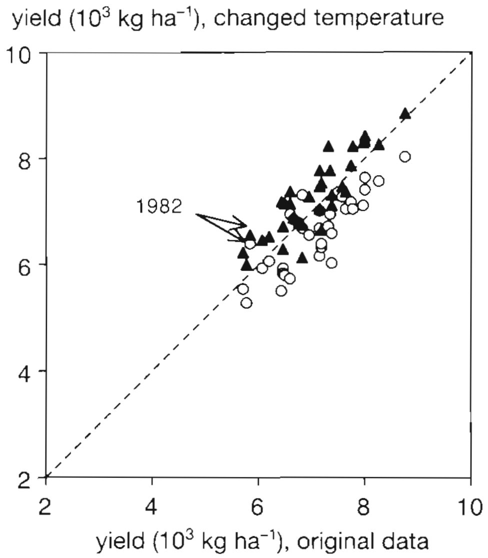

Fig. 4. Comparison between spring wheat yield simulated with the original data set (Wageningen, 1954 to 1987) and simulated yield when temperature in this data set was underestimated (▲) or overestimated (O) by 1 °C

mation of the yield, and in the other half in overestimation of the yield. In 1982 both over- and underestimation of temperature resulted in an increase in simulated yield. The effect of an increase in temperature from −6 °C to +6 °C on simulated yield using daily data from 1982 and the climatic averages is shown in Fig. 5.

Completely different effects were found when climatic averages or daily data were used. With climatic averages, overestimation of temperature led to a decline in yield, a small underestimation of 1 °C led to an increase, and a larger underestimation resulted again in a decrease. With daily weather data from 1982, over- as well as underestimation of temperature by 2 °C resulted in a yield increase; larger over- or underestimations had only a small effect on simulated yield.

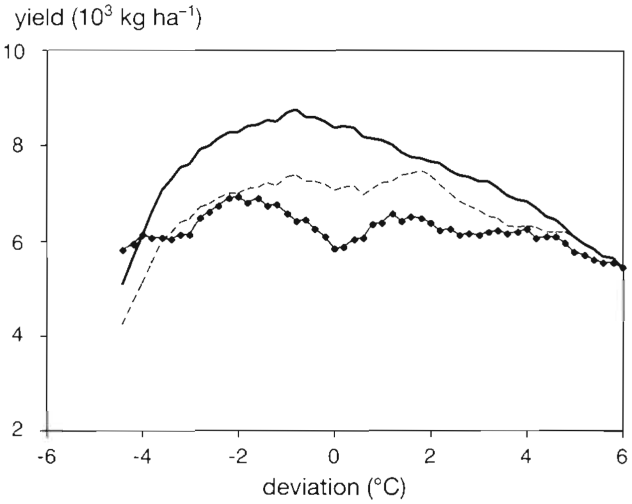

Fig. 5. Effect of a deviation in temperature of up to 6 °C on simulated spring wheat yield when climatic averages (——), daily weather data from 1982 (◆–◆–◆) and climatic averages with adjusted radiation values (see text) (- - - -) were used as input

The mean daily air temperature based on 30 yr averages shows a sinusoidal curve over the year, gradually increasing in spring and decreasing in autumn (Fig. 6A). (This was also observed for daily global radi-

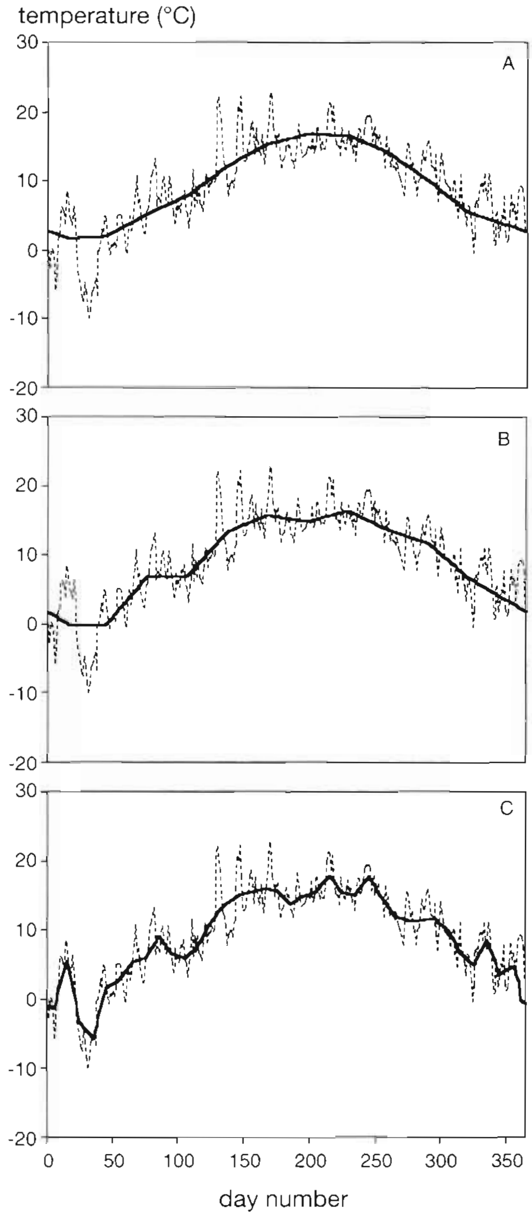

Fig. 6. Comparison between mean daily temperature [$0.5 \times (T_{max} + T_{min})$] in 1954 in Wageningen (-----) and estimated values (——) based on (A) climatic averages, (B) monthly averages, and (C) 10 d averages

ation; see Fig. 16A.) When temperature during the growing season shows such a curve, the observed impact of over- and underestimation of temperature on duration of vegetative period and on final yield can be explained easily. A small underestimation of temperature results in later crop emergence, a longer vegetative period (at higher radiation levels) and, thus, a higher yield (Figs. 3 & 5). When underestimation is more than 1 to 2 °C, too much of the grain filling period occurs during the period of low radiation levels in autumn, and yield is reduced. When temperature is underestimated by more than 4 °C, the crop does not mature before the end of the year. An overestimation of temperature leads to a shorter vegetative period and a lower yield. The optimum in the yield curve for 30 yr averages (Fig. 5) lies very close to the actual temperature (a deviation of 0 °C). However, it cannot be concluded that the present situation is the only optimal one. Spring wheat variety and sowing date in the model are adapted to the present situation. Deviation from this situation results, therefore, in a lower yield. Other varieties and sowing dates are required to obtain high yields under changed conditions.

The course of the actual temperature over the year can differ substantially from the 30 yr average (Fig. 6A), causing changes in temperature to have an unexpected effect on simulated yield and vegetative period duration, as was shown for 1982 and 1973. For 1973, the strange effect of a decrease in temperature on duration of the vegetative period was caused by the occurrence of a period of very low temperatures just after crop emergence. With the original data (i.e. no deviation) the crop emerges just before a period of very low temperatures starts. During this cold period the development of the crop comes to a standstill and the vegetative period of the crop is prolonged. However, when temperature is underestimated, the crop has not emerged at the moment the cold period starts and thus emergence is delayed until the cold period is over. Emergence after the cold period implies that vegetative development is not delayed by the low temperatures, resulting in a shorter vegetative period. For 1973, underestimation of only 1 °C leads to a difference in vegetative period duration of 10 d. By changing the temperature data in the set with climatic averages this effect can be reproduced. In the simulation run with climatic averages the crop emerges on April 1. Merely by reducing minimum and maximum air temperatures to, respectively, 0 and 5 °C on April 2 to 11 the same effect of temperature underestimation on vegetative period duration is achieved (Fig 3).

The explanation for the local minimum in the curve for simulated yield in 1982 is found in a period of unfavourable weather conditions (low temperature and low radiation) just before flowering of the crop. An overestimation of temperature leads to earlier crop emergence and earlier flowering, so that the unfavourable weather period occurs during the grain filling period of the crop. The model is less sensitive to unfavourable weather conditions during the grain filling period than during the vegetative period, and thus a yield increase is obtained. The longer vegetative period resulting from underestimation of temperature compensates for the effect of the adverse weather conditions in this period, resulting in a yield increase. The local minimum as found for 1982 can be reproduced by decreasing global radiation (in the set with climatic averages) to 5 MJ m^{-2} d^{-1} in the 10 d before flowering of the crop (June 9 to 18) (Fig. 5).

The model is rather sensitive to inaccuracies in temperature. An underestimation of only 1 °C can result in a change in duration of the vegetative period of 10 d in some situations. Since inaccuracies can have such a large effect on the simulation results, it is vital to replace missing values by realistic data.

For all estimation methods considered, the average deviation from the original values was calculated according to 2 equations (Table 1). The values in Table 1 are calculated for the period 1976 to 1985. For these years data from all estimation methods were available. The deviations in the first 2 columns indicate whether temperatures are, on average, higher or lower than the original value. Deviations in columns 3 and 4 are comparable to the standard deviation of a population and are measures of the absolute difference from the original data. Since averages over 10 d and monthly averages are derived from the daily data, the average temperatures are the same, and the deviations in columns 1 and 2 are zero (Table 1). Climatic averages are based on daily data from 1954 to 1983, for

Table 1. Average deviation in temperature (°C) between the original value (x_{oi}) on Day i in the Wageningen data set and the estimated value (x_{ei}), for minimum (T_{min}) and maximum (T_{max}) temperature for various estimation methods, where n is the number of days (3650 = 10 yr × 365 d). Methods considered are: data from another station (De Bilt, De Kooy) and average values from Wageningen over various intervals (10 d, 1 mo, or 30 yr climatic averages)

	$\frac{\sum_{i=1}^{n}(x_{oi}-x_{ei})}{n}$		$\sqrt{\frac{\sum_{i=1}^{n}(x_{oi}-x_{ei})^2}{n}}$	
	T_{min}	T_{max}	T_{min}	T_{max}
De Bilt	−0.4	−0.4	1.8	2.0
De Kooy	−1.2	1.1	2.7	2.7
10 d averages	0	0	2.9	2.8
Monthly averages	0	0	3.5	3.6
Climatic averages	−0.3	−0.2	3.8	4.0

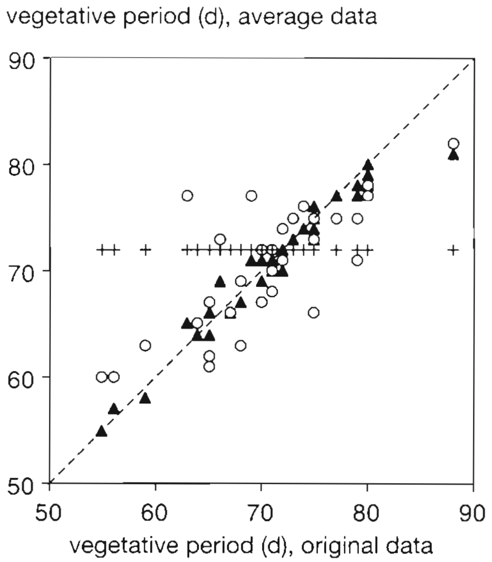

Fig. 7. Comparison between duration of the spring wheat vegetative period simulated with the original data set (Wageningen, 1954 to 1987) and duration of this period when temperature values were estimated from average data: (▲) 10 d averages, (O) monthly averages, (+) climatic averages

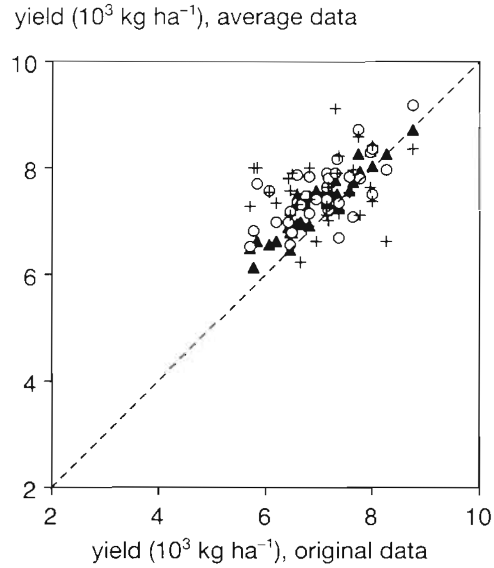

Fig. 8. Comparison between spring wheat yield simulated with the original data set (Wageningen, 1954 to 1987) and simulated yield when temperature values were estimated from average data: (▲) 10 d averages, (O) monthly averages, (+) climatic averages

which the average temperature is not equal to the average of the daily data. The minimum temperature in De Kooy is higher than in Wageningen and the maximum is lower, due to the effect of the sea. Both maximum and minimum temperature in De Bilt are 0.4 °C higher than in Wageningen. However, deviation in column 3 or 4 gives a different picture: deviation of the data from the data at De Bilt and De Kooy is smaller than that from the average data. The deviation increases with increasing length of the averaged interval. This is in accordance with the data shown in Fig. 6: the temperature data based on 10 d averages give a better estimate of the daily values than do averages over longer intervals, but large differences remain. It is striking that the average over 10 d gives a larger deviation from the original values than data from a station 130 km away. This phenomenon was also found by Kemp et al. (1983): estimates for missing temperature data based on data from a nearby station produced smaller deviations from the original values than did estimates based on average values from the station itself.

In Figs. 7 & 8 the effect of using average temperature data on simulation results is shown. Use of averages over 10 d gave the smallest deviation in simulation results. The deviation in duration of the vegetative periods was on an order of magnitude of days. Use of climatic averages implies that temperature was the same in all years, for which simulated duration of the vegetative period was therefore the same (72 d). Actual temperatures can be quite different, leading to differences in duration of over 20 d. Use of monthly averages resulted in a deviation in simulated duration of 5 to 10 d. Overestimation of the yield by 25% occurred when climatic averages or monthly averages were used. Averages over 10 d gave a smaller deviation. These results imply that it is not advisable to use average data for estimation of missing values.

Use of data from another station gave far better results. Deviations of ca 5% were obtained when data from De Bilt were used (Figs. 9 & 10). Data from De Kooy resulted in a larger deviation.

Randomly replacing 10% of the daily data by climatic averages had hardly any effect on simulation results. So, when only a few data are randomly missing, there is no need to pay special attention to the estimation procedures. Missing data, however, are often clustered, since it takes several days to repair the instruments. It was shown that in some years even as few as 10 d of incorrect data had large effects on simulation results. When missing values are clustered, it is better to replace them by data from a nearby station.

GLOBAL RADIATION

Nature and availability of the data

Global radiation includes both direct and diffuse solar radiation and is an important weather variable for

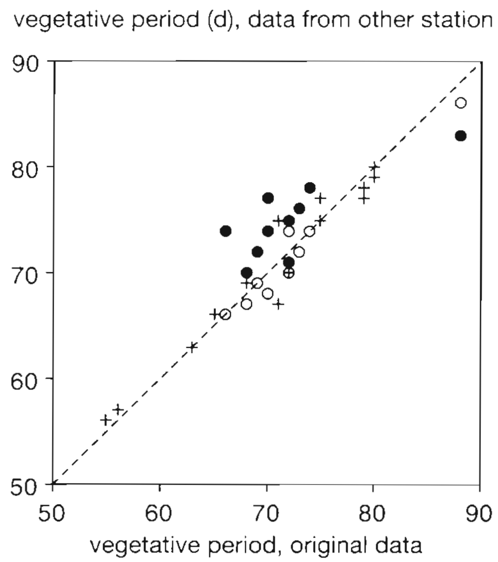

Fig. 9. Comparison between duration of the spring wheat vegetative period simulated with the original weather data set (Wageningen, 1961 to 1987) and duration of this period when temperature values in this set were replaced with data from another meteorological station: (O) De Bilt, 1976 to 1985; (●) De Kooy, 1976 to 1985; (+) De Bilt, 1961 to 1975 and 1986 to 1987

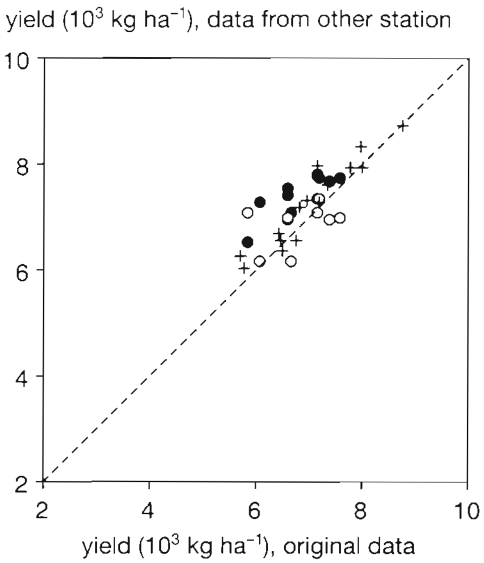

Fig. 10. Comparison between spring wheat yield simulated with the original weather data set (Wageningen, 1961 to 1987) and simulated yield when temperature values in this set were replaced with data from another meteorological station: (O) De Bilt, 1976 to 1985; (●) De Kooy, 1976 to 1985; (+) De Bilt, 1961 to 1975 and 1986 to 1987

agricultural research, since this type of radiation provides the energy for crop growth. Not all wavelengths within the global radiation spectrum can be used for photosynthesis: only photosynthetically active radiation (PAR, 400 to 700 nm) provides the energy for photosynthesis. SUCROS87 assumes that half of the global radiation consists of PAR (Spitters et al. 1989). The basis for calculating crop photosynthesis is the photosynthesis-light response curve of individual leaves of the crop (de Wit 1965, Goudriaan & van Laar 1978). Since this relation is not linear, average radiation does not result in average photosynthesis (Fig. 11).

The instruments for measuring global radiation were developed during the 1920s (Moll 1923, Gorczynski 1926, van Gulik 1927). In the late 1920s regular measurements were started in Wageningen (van Gulik 1929). In the early 1940s global radiation was also measured in Rothamsted, England, and in Versailles, France. Since the 1960s the number of sites where global radiation is recorded has increased, but presently global radiation is still measured at only a small number of meteorological stations. In some countries 2 different networks exist: one maintained by the national meteorological institute (measuring temperature, rainfall, etc.) and a second one maintained by the national institute for solar energy (measuring several types of solar radiation, including global radiation). Accordingly, global radiation data are often published separately from temperature and rainfall data.

The fact that long-term records of global radiation are available from only a very few sites in Europe, and that even today this variable is recorded at only a few sites, makes global radiation the limiting factor in most weather data sets. In the last decade several methods for estimating global radiation data have been published. Global radiation may be estimated from other weather variables such as sunshine duration, air temperature and rainfall (Bristow & Campbell 1984, McCaskill 1990, Bindi & Miglietta 1991), by interpolation of data from other sites

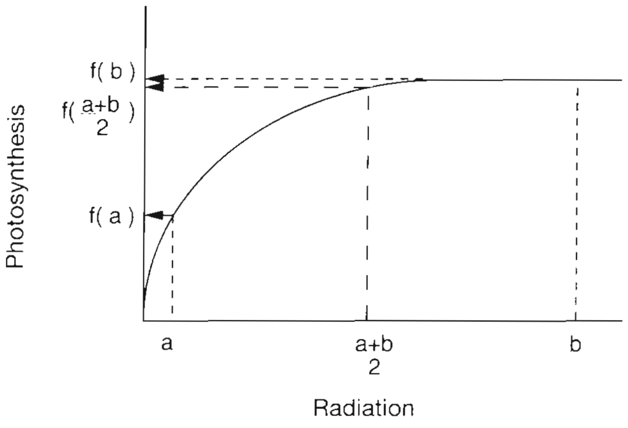

Fig. 11 Form of the photosynthesis-light response curve, and the effect of using average radiation data on the calculated assimilation

(Suckling 1985), or from satellite information (Frulla et al. 1988, Ben Djemaa & Delorme 1992, Delorme et al. 1992).

Usually, sunshine duration data are used for estimation of global radiation. Therefore, in this paper, besides the effects of the same estimation methods that were applied to temperature, attention is paid to the effects of using sunshine duration data instead of global radiation data on simulation results.

Sunshine duration (hours of bright sunshine per day) is recorded at far more locations than global radiation. In The Netherlands 35 stations record sunshine duration, and 23 record global radiation (Velds 1992); in former West Germany the numbers are 68 and 8 (Golchert 1981), in Great Britain 132 and 25 (Cowley 1978) and in Italy 70 and 28 (Andretta et al. 1982). Sunshine duration and the amount of global radiation are directly related (on a day with a large number of hours of sunshine, global radiation is high).

To estimate global radiation the so-called Ångström formula was used (Ångström 1924, Prescott 1940):

$$\frac{Q}{Q_0} = A + B\frac{n}{N} \tag{1}$$

where Q is the global radiation (J m^{-2} d^{-1}), Q_0 is the total radiation in the absence of the atmosphere (J m^{-2} d^{-1}), n is the recorded hours of bright sunshine and N is the astronomical daylength (h). The coefficients A and B are site-dependent and are affected by optical properties of the cloud cover, ground reflectivity and average air mass (Iqbal 1983). Values of A and B have been derived for many locations (Cowley 1978, Golchert 1981, Martínez-Lozano et al. 1984, Palz 1984).

From De Bilt both global radiation and sunshine duration data were available on a daily basis (1961 to 1980). These data were used to study the effect on simulation results of estimating global radiation based on hours of sunshine. A and B values for De Bilt (0.20 and 0.55 respectively) were obtained from the European Solar Radiation Atlas (Palz 1984). Two simulation runs were made with the weather data from De Bilt: one with the recorded global radiation data, and one with the estimated global radiation based on sunshine duration data (Eq. 1).

Global radiation can be recorded with several different instruments (Fritschen & Gay 1979, Velds 1992). The series in Wageningen is recorded with the Kipp-Solari meter (van Gulik 1927, de Vries 1955). When this type of instrument is maintained well, inaccuracy is limited to 5% (Bener 1951). de Vries (1955) found random errors of 5% and systematic errors of 1 to 10% for the instrument used in Wageningen. Here, the effect of a 10% inaccuracy in global radiation data is studied.

Results and discussion

Effects of global radiation inaccuracies

Underestimation of global radiation by 10% resulted in a decline in yield (grains, dry matter) of 5 to 10% (Fig. 12) and overestimation in an increase in yield of about 5% in most years. There were small differences in sensitivity between the years: in 1976 overestimation of radiation resulted in a yield increase of only 3% and underestimation in a yield decline of 5%, while in 1961 overestimation resulted in a yield increase of 8% and underestimation in a yield decline of 10%.

To achieve a better understanding of the effects of inaccuracies in global radiation data on simulation results in various years, the sensitivity of the model to deviations of up to 6 MJ m^{-2} d^{-1} was studied for the years 1961 and 1976. Sixty simulation runs were made for each year. In the first run, daily total global radiation was decreased by 6 MJ m^{-2} d^{-1} on all days; in each following run the deviation in global radiation was altered by 0.2 MJ m^{-2} d^{-1} up to an overestimation of 6 MJ m^{-2} d^{-1}. The results of these simulation runs are plotted in Fig. 13. In 1976 overestimations of up to 6 MJ m^{-2} d^{-1} had no effect on simulated yield; an underestimation of 6 MJ m^{-2} d^{-1} resulted in a yield decline of 2 t ha^{-1}. In 1961 overestimation resulted in a yield increase of 1.5 t ha^{-1}, and underestimation in a yield decline of 4 t ha^{-1}.

The effects of over- and underestimation of radiation in different years can be explained by the form of the

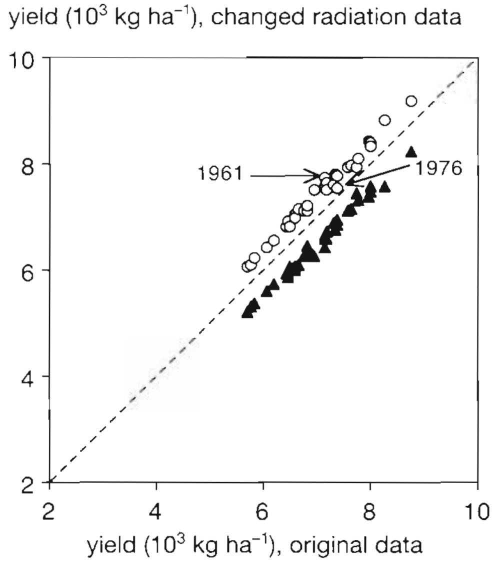

Fig. 12. Comparison between spring wheat yield simulated with the original weather data set (Wageningen, 1954 to 1987) and simulated yield when global radiation was (O) overestimated or (▲) underestimated by 10%

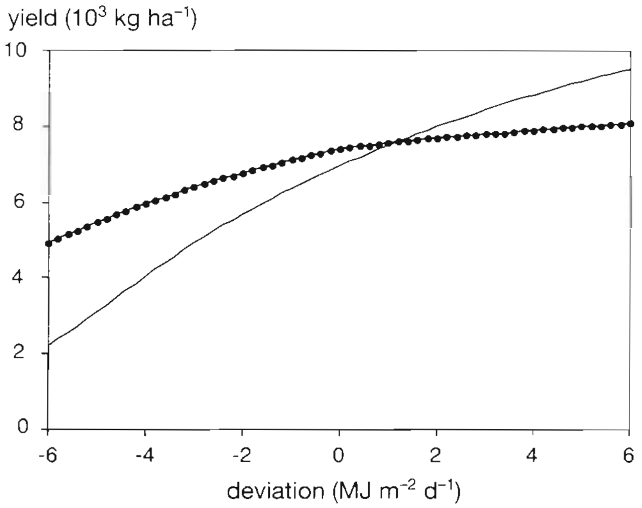

Fig. 13. Effect of deviations in global radiation of up to 6 MJ m^{-2} d^{-1} on simulated spring wheat yield, using daily weather data from Wageningen in 1976 (●-●-●) and 1961 (——)

photosynthesis-light response curve (Fig. 11). At high radiation levels saturation occurs; hence, inaccuracies at high radiation levels have no effect on photosynthesis and crop yield. There are large differences in radiation levels between growing seasons. In some years average radiation during the vegetative period is just over 12 MJ m^{-2} d^{-1}, while in other years average radiation levels over 18 MJ m^{-2} d^{-1} are recorded (Fig. 14). In 1976 radiation levels were high, so inaccuracies had little effect on crop production, whereas in 1961 levels were low, so inaccuracies in global radiation had a larger effect on crop production.

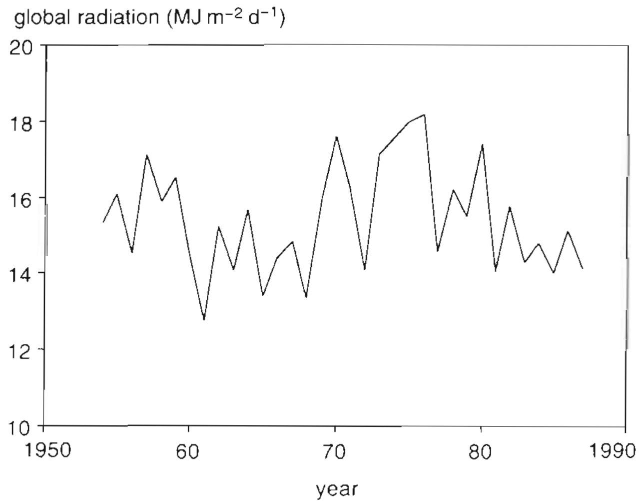

Fig. 14. Average daily global radiation during vegetative period of the spring wheat crop when daily weather data from Wageningen were used as input in the simulation model

Estimation of missing values

In Table 2 the average deviation from the original global radiation values (recorded in Wageningen, 1976 to 1985) is given for the various estimation methods considered. Since averages over 10 d or over 1 mo are obtained from the original daily values, these average radiation levels are the same, resulting in zero deviation in the first column. The climatic data are based on data from 1954 to 1983 and cover a different period, so that a small difference in average radiation levels results. Since no sunshine duration data from Wageningen were available, deviation due to use of sunshine duration data is based on measurements from De Bilt (1961 to 1980). The deviation from the original value is smallest when sunshine duration data are used.

There is a gradient in radiation levels over the country, with levels increasing towards the west (Velds 1992). Differences in radiation of 5 to 10% are found between De Bilt and Wageningen (Prins & Reesinck 1948), and differences greater than 10% between De Kooy and Wageningen (Prins 1944). This gradient is reflected in the difference in average radiation levels between Wageningen, De Bilt and De Kooy (Table 2). Radiation levels in De Kooy are on average 1 MJ m^{-2} d^{-1} higher than in Wageningen. Since radiation levels in De Bilt and De Kooy are on average higher than in Wageningen, it is not surprising that use of these data results in an overestimation of simulated yield (Fig. 15). The overestimation of yield by using data from De Kooy is of the same order of magnitude as that due to 10% overestimation of radiation (Figs. 12 & 15), which is in accordance with the fact that radiation lev-

Table 2. Average deviation in global radiation (MJ m^{-2} d^{-1}) between the original value (x_{oi}) on Day i and the estimated value (x_{ei}) for various estimation methods. Methods considered are: data from another station (De Bilt, De Kooy), averaged data from Wageningen over various intervals (10 d, 1 mo, and 30 yr climatic data) and estimates based on sunshine duration data (see text). n is the number of days (7300 for sunshine duration data and 3650 for the other estimation methods)

	$\frac{\sum_{i=1}^{n}(x_{oi}-x_{ei})}{n}$	$\sqrt{\frac{\sum_{i=1}^{n}(x_{oi}-x_{ei})^2}{n}}$
De Bilt	-0.3	3.0
De Kooy	-1.0	4.0
10 d averages	0	3.8
Monthly averages	0	4.2
Climatic averages	0.1	4.4
Sunshine duration	-0.1	1.4

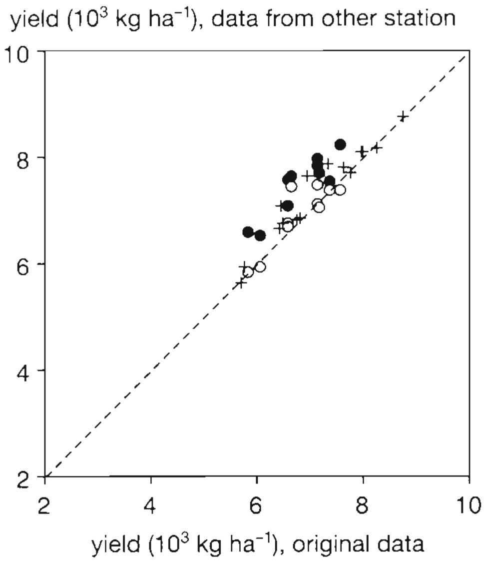

Fig. 15. Comparison between spring wheat yield simulated with the weather data from Wageningen (1961 to 1987) and simulated yield when global radiation data were obtained from another meteorological station: (O) De Bilt, 1976 to 1985; (●) De Kooy, 1976 to 1985; (+) De Bilt, 1961 to 1975 and 1986 to 1987

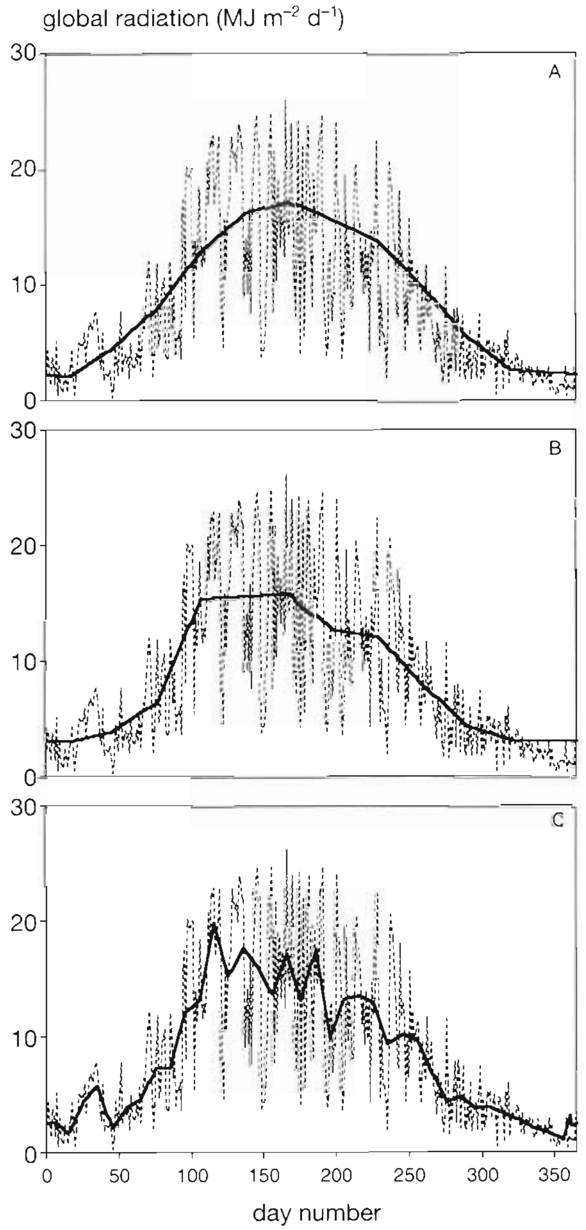

Fig. 16. Comparison between the measured daily global radiation in 1954 in Wageningen (-----) and the estimated values (——) derived from (A) climatic averages, (B) monthly averages and (C) 10 d averages

els are 10% higher in this part of the country. However, use of averages over 10 d or 1 mo as estimates also resulted in overestimation of yield, even though these average levels are identical to daily averages of the original data. This overestimation is due to the very large variability in daily total global radiation (Fig. 16). When large differences exist, use of average values leads to overestimation of photosynthesis (Fig. 11). Furthermore, large differences in radiation levels between individual years (Fig. 14) ensure that estimates based on climatic averages have little to do with the original value. In some years use of climatic averages gives the same simulation result as use of the original data set, but in most years there is an overestimation (Fig. 17). Use of climatic averages implies that radiation levels are the same in all years. Differences in simulated yield in various years are due to differences in temperature (note that only values for global radiation are estimated; the temperature data are the original daily values), through which differences in duration of the growing season exist, resulting in differences in the amount of radiation intercepted by the crop.

Data from De Bilt gave reasonable simulation results in most years. Use of radiation data from a nearby station is, however, not a realistic solution for replacing missing values. As mentioned before, global radiation is recorded at only a limited number of meteorological stations, so it is very unlikely that data will have been measured at more than one site in the same climatic district.

Use of sunshine duration data from the same station to estimate missing values is therefore the best solution (Fig. 18). However, several versions of the Ångström formula (Eq. 1) are in use. Some authors define daylength (N) as the value which the sunshine recorder will record on a completely clear day. Using this definition, daylength is much shorter, since sun-

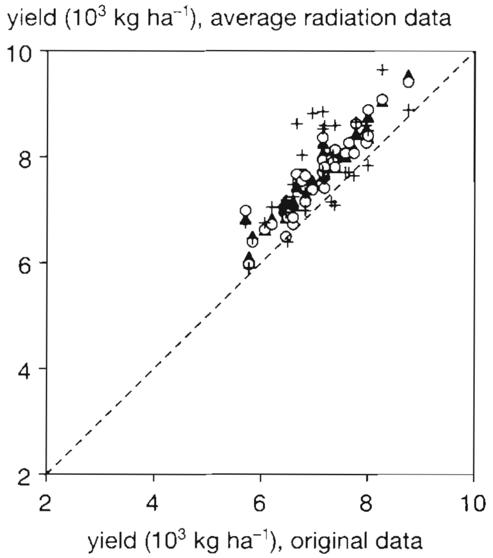

Fig. 17. Comparison between simulated spring wheat yield using daily weather data (Wageningen, 1954 to 1987) and simulated yield when average values for global radiation from this station were used: (▲) 10 d averages, (O) monthly averages, (+) climatic averages

shine recorders often do not record sunshine when the sun is less that 5° above the horizon (Iqbal 1983). In addition, several definitions for Q_0 are used (Martínez-Lozano et al. 1984). The use of different definitions for N and Q_0 necessitates other values for A and B, so care should be taken when A and B values are obtained from the literature. Another important consideration is that sunshine duration is often recorded with a Campbell-Stokes sunshine recorder, which has inaccuracies of up to 20% (Painter 1981). Accordingly, the inaccuracies in sunshine duration data can be quite large.

In the literature, average deviations between estimated and recorded radiation of 2 to 5 MJ m^{-2} d^{-1} are given for other estimation methods. Estimates on the basis of satellite information are the best, with a deviation of around 2 MJ, while for the other methods deviations of over 5 MJ are found. This deviation is comparable with that due to use of data from De Kooy to estimate global radiation in Wageningen (Table 2, column 2); deviations in simulated yield of 20% in some years can therefore be expected with these methods. This deviation in simulated yield was also found by Bindi & Miglietta (1991), who developed an estimation method for global radiation based on temperature and rainfall data and studied the effects of this estimation on the simulation results of a winter wheat model. Deviations in simulated yield of 20% were found for some locations in some years.

When 10% of the global radiation data were replaced randomly by climatic averages, hardly any effect was found on simulated yield. This phenomenon was also found for the temperature data. So, when only a few data are missing randomly, no special attention need be paid to the estimation procedure. However, as soon as the missing data are clustered, care should be taken: it was shown that incorrect values of global radiation during the 10 d before flowering of the crop have a large effect on final simulated yield.

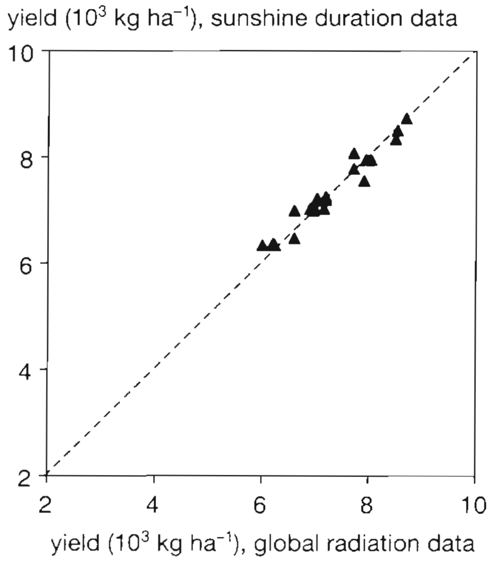

Fig. 18. Comparison between spring wheat yield simulated using daily weather data from De Bilt (1961 to 1980) and the simulated yield when global radiation was estimated from sunshine duration data from this station

DATA FOR ALL VARIABLES TAKEN FROM ANOTHER STATION

Why the data are used

When a simulation model is used in combination with a field experiment, in principle, weather data from this field are required to simulate the production in the experiment. In practice, the weather data are obtained from a nearby weather station, so that differences exist between the weather conditions at the field experiment and at the weather station. The effect of using data from a distant station was studied by running the model with the complete data sets from De Bilt (1961 to 1987) and De Kooy (1976 to 1985).

Results and discussion

The average simulated yield was the same when weather data from Wageningen or De Bilt were used

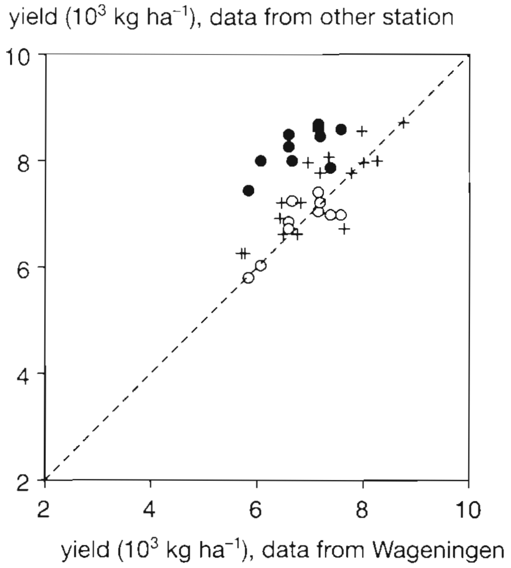

Fig. 19. Comparison between potential spring wheat yield simulated with the weather data from Wageningen (1961 to 1987) and the yield simulated with the complete weather data from: (O) De Bilt, 1976 to 1985; (●) De Kooy, 1976 to 1985; (+) De Bilt, 1961 to 1975 and 1986 to 1987

(Fig. 19). However, in individual years, differences in simulated yield of 2 t ha^{-1} occurred. When weather data from De Kooy were used, the average simulated yield was higher than when Wageningen data were used (Fig. 19).

The large deviation in simulated yield when data from De Kooy are used is not surprising: it was shown that individual weather data from De Kooy cannot be used to replace missing values in the data set. Individual data from De Bilt were found to represent good estimates for missing values from Wageningen; however, using the complete data set from De Bilt resulted in important deviations in simulated yield. The explanation for this is that weather variables are related — when radiation level is different it is very likely that temperature is different too, and in some circumstances the effects will be additive so that a large deviation in simulation results can occur.

CONCLUSIONS

Differences in temperature of 1 °C, and in global radiation of 10%, between a meteorological station and a given field experiment can be expected. These differences can cause a deviation in simulated yield of up to 1 t ha^{-1}. Due to the irregular course of temperature and radiation, the use of averages is unsuitable for simulation of crop production on a daily basis. Use of these data nearly always results in an overestimation of yield in comparison with yield simulated with daily values. Missing temperature values in a data set can best be replaced by data from another meteorological station located in the same climatic district. It is best to replace missing global radiation data with estimates based on sunshine duration data.

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